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Precision Power Supply Control Module

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ABSTRACT

A temperature stabilized, digital input circuit module using surface mount technology has been developed for use as the precision control element in a 10 A bipolar trim magnet regulator. Regulators using this module have shown stability of 20 ppm over 8 hours. This circuit module combines the functions of a current measuring shunt, serial DAC, precision voltage reference, high gain error amplifier and readback buffer amplifier. Loop gain and compensation are done externally to the module. The module can be used in high current power supplies by replacing the internally derived current signal with the output signal from an external high current shunt or transductor.

INTRODUCTION

The power supplies which provide currents to approximately 1900 focussing and steering magnets in the CEBAF recirculating electron accelerator will periodically be adjusted based on measurements from numerous beam monitors located around the accelerator. Initially, power supplies with 1000 ppm combined drift and ripple performance were considered adequate to drive these magnets. This level of performance was achievable using readily available devices and well understood analog techniques without need for stringent temperature control measures.

Further analysis of beam dynamics indicated that power supplies with 100 ppm ripple performance were needed. This level of performance required that an entirely different approach be taken for the low level power supply control circuitry.

The key component was the current sensor which provides a feedback signal to the error amplifier. Even a good shunt resistor, such as one made of manganin, has a temperature coefficient of about 15 ppm/°C. Resistance drift over 24 hours due to expected ambient temperature change alone would more than use up the entire error budget. A zero-flux transductor was considered for the current sensing device but was rejected because the size and cost were too high for this application. Hall effect devices were rejected because of temperature stability and noise considerations.

The only feasible choice turned out to be a shunt resistor tightly coupled to a thermally regulated substrate which isolates the shunt from ambient temperature fluctuations and minimizes the effect of self-heating. The first effort in this direction combined a manganin shunt resistor and a preamplifier which were both mounted on a temperature regulated aluminum block. This isothermal block was mounted on a backplane and the high level feedback signal from the preamplifier was routed to the power supply printed circuit board through a backplane mounted connector.

It then became clear that it is very desirable to combine all temperature sensitive devices on the same isothermal block and mount the "core controller" block right on the power supply printed circuit board. This approach gives very good thermal performance as well as minimizing the amount of EMI which can be coupled into the low level regulation circuitry. Because the monitoring and control of each power supply module was being done with an on-board microprocessor and signal convertors, it was possible to closely connect the core controller to the necessary signal processing circuitry. Figure 1 shows a simplified schematic of the entire regulator.

DETAILED DESCRIPTION

Since beam variables, as measured by the beam monitors, are the controlled parameters, the magnet power supplies need not have particularly high absolute accuracy. A requirement of 0.1% FS (full scale), absolute accuracy was established based on interchangeability and diagnostic considerations. More important than accuracy are resetability and stability. Based on extensive modeling of CEBAF beam dynamics, minimum targets of 14 bit monotonicity and 100 ppm total envelope of uncertainty (drift plus peak-to-peak noise and ripple) per eight hour shift were chosen. The two major error components, noise and temperature induced drift, were tentatively budgeted at 34 ppm, peak-to-peak, and 2.5 ppm/°C respectively.

The stability of a high precision, current regulated power supply is usually limited by the quality of the current sensor used as the feedback device. The two most common high precision current sensors are zero flux magnetic transductors and resistive shunts. Zero flux transductors were rejected because of cost and size considerations. Initial investigation and experiments with conventional resistive shunts indicated that the temperature coefficient of resistivity and thermoelectric effects were unacceptably high.

To achieve the necessary noise and drift goals for the CEBAF power supplies, a new packaging and circuit architecture were developed by Highland Technology, Inc. A "core" power supply controller (patent applied for) was designed which combines a precision current shunt, preamplifier, serial DAC, voltage reference, error amplifier and support electronics into a single, temperature stabilized

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assembly. A simplified schematic of the core controller is shown in Figure 2, and its physical layout is shown in Figure 3. The controller is fabricated on a solid aluminum block to which are bonded a planar current shunt, a surface mount circuit board, a temperature sensor and a heating element. The shunt preamplifier, DAC, error amplifier, associated voltage regulators and the temperature control loop components are mounted on the circuit board so that all components are very tightly coupled thermally to the temperature controlled aluminum baseplate. The magnet load current, which may be as much as 10 A, is connected to the controller through two of the metallic mounting standoffs. Low level signals pass through a small 12 pin connector. A 16 bit serial input DAC was chosen to minimize data connections and their associated thermal leakage paths. The feedback compensation elements of the error amplifier were not included on the controller assembly to allow external control of power supply control loop dynamics.

Integration of all sensitive components into a temperature regulated assembly provides substantial reduction of temperature coefficient and thermoelectric error sources. Such effects are reduced by the effective "stiffness" of the thermal control loop (ambient temperature change divided by assembly temperature change) which is about a factor of 100. It is interesting to compare this current controller design to a typical "ovenized" electronics package which might be used for something like a crystal oscillator which does not dissipate much heat. In the case of the current controller, the heat from the resistive current shunt is a major error source to the temperature control loop of the isothermal block and can potentially cause severe temperature gradients within the assembly. Unlike the case of the crystal oven, the current controller design requires much lower thermal resistances between all components and must be packaged to allow a predictable heat leak to the ambient environment so that shunt power dissipation cannot push the temperature control loop out of regulation.

The final current controller design operates at 68°C and dissipates about 5 W under normal operation. The shunt element is punched from sheet manganin and contributes about 0.7 W at full scale output current of 10 A. The controller package is plugged onto the main power supply card and is held in place with four screws. The core controller assembly is covered with a phenolic potting shell giving an overall size of 3×3×0.75 inches.

CONTROL LOOP DYNAMICS

The accelerator focus and steering magnets vary in inductance from 40 mH to about 1 H with typical resistances in the 2 ohm range. It was desired to configure the control loop dynamics to allow a single power regulator card design to drive any magnet while simultaneously providing high stability margins and minimum noise levels. Current regulation is achieved by the overall type 1 (integrating) feedback loop with the RC network and the magnet L/R time constant dominating closed loop dynamics. The output amplifier and power booster stages employ two additional inner feedback loops to insure that the output stage performs as a very stiff, wideband voltage amplifier with good local power supply ripple rejection. The use of local output stage feedback allows the overall current control loop to be optimized on loop stability and noise bandwidth considerations without concern for power supply noise or output stage drifts. The RC compensation was chosen to provide integration at low frequencies, leveling off to a flat loop gain of 1500 at about 0.3 Hz with the magnet's effective L/R time constant providing the final 6 db/octave rolloff. The resulting current regulator has excellent phase margin for all required magnet loads. The output impedance of the regulator makes a smooth transition from a high value (corresponding to a constant current mode) at low frequencies to a low value (corresponding to a constant voltage mode) at high frequencies. This restricts loop noise bandwidth and allows the magnet L/R time constant to participate in attenuating high frequency noise and ripple.

PERFORMANCE

Because the controller is meant to be part of a high gain feedback loop, as well as requiring a serial data input link, it is difficult to test it as an isolated device. Instead, all but the simplest testing was done with the device installed in a fully functional power supply module.

Key power supply performance parameters are DC current stability, power line harmonic rejection, low frequency noise and resetability. High frequency noise is of less concern because of the filtering effect provided by the L/R time constant of the magnets.

DC current stability, low frequency noise and resetability were measured using a precision transductor and an $8\frac{1}{2}$ digit DVM. The particular DVM used had automatic sampling, storage and analysis capability which allowed substantially more data acquisition and analysis to be done than is normally the case with a DVM. A temperature coefficient of about 2 ppm/°C was calculated based on tests run over several days.

Resetability was measured at +/- 2 A, +/- 4 A, +/- 6 A, +/- 8 A. The test method used sent a current command to the power supply, read the zero flux transductor output with the DVM and then sent a command of the opposite polarity to the power supply. This cycle was repeated numerous times and the data used to plot resetability histograms which showed a spread of less than 5 ppm.

Current ripple was measured by using a FFT (Fast Fourier Transform) analyzer to generate the frequency spectrum seen at the output of the transductor electronics. To generate a worst case estimate, the harmonic components were directly added to derive the current ripple. The FFT spectra are additionally useful because of information gained by knowing what line frequency harmonics are present although a time domain trace of the current ripple would be very useful because it would be a much easier method of checking if the power supply was meeting ripple specifications. Currently work is underway to set up instrumentation capable of furnishing a time domain trace of current ripple. Figure 4 shows a typical output frequency spectrum.

The temperature coefficient is less than 2 ppm/°C with a worst case peak-to-peak current noise envelope of about 50 ppm of magnet FS current. Some small nonlinearities and thermal effects are observed, probably caused by thermally induced stresses and residual thermal gradients. These effects are in the 10 ppm range and of no consequence. Some of the regulators have shown a worst case 60 Hz ripple of about 40 ppm which is thought to be largely due to stray magnetic field pickup due to positioning in the relay rack.

The power supply drift over a 24 hour period with a 28°C ambient temperature swing is in the 50 ppm range.

In addition to the development and evaluation testing of the design itself, each core controller is extensively tested at the factory as well as passing through an acceptance test at CEBAF.

EXTENDED USE

Although the controller was primarily developed for use in relatively small corrector and focussing magnet power supplies, it will find widespread use at CEBAF as the key element in a standard control module which will include all low level circuitry necessary for any size of power supply. For use with high current power supplies it will be necessary to disconnect the internal shunt preamplifier output and introduce an external high level feedback signal from a transductor or high power shunt.

The present controller unit will give 100 ppm performance over a fairly wide ambient temperature swing while 10 ppm drift performance is possible by enclosing the entire low level regulator module in a temperature controlled environment and using a transductor with a suitably low temperature coefficient.

SUMMARY

A temperature regulated core controller has been developed for use in a 10 A, bipolar corrector power supply which gives better than 100 ppm performance over a wide ambient temperature range. The controller combines a precision shunt, preamplifier, serial DAC, voltage reference and error amplifier in a compact, printed circuit board mountable package. Use of the controller can be extended to any size power supply by using an externally generated feedback signal rather than relying on the internal shunt and preamplifier.

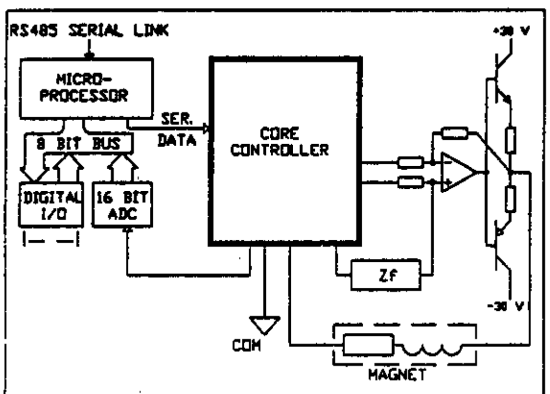
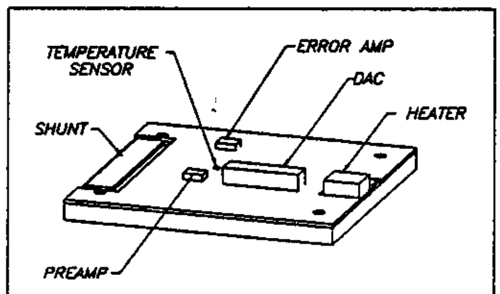


FIG. 1 - CURRENT REGULATOR DIAGRAM



CONTROLLER PHYSICAL LAYOUT
FIGURE 3

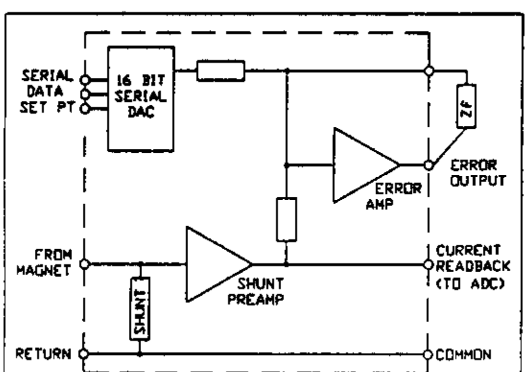


FIG. 2 - CORE CONTROLLER SCHEMATIC

TRIM SYSTEM - 8 AMP OUTPUT

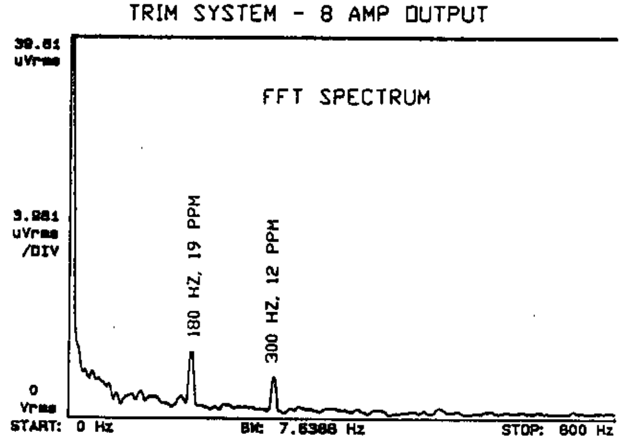


FIG. 4